

Results and prospects of deep under-ground, under-water and under-ice experiments

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Abstract

Astroparticle experiments have provided a long list of achievements both for particle physics and astrophysics. Many of these experiments require to be protected from the background produced by cosmic rays in the atmosphere. The main options for such protection are to build detectors deep under ground (mines, tunnels) or in the deep sea or antarctic ice. In this proceeding we review the main results shown in the RICAP 2013 conference related with these kind of experiments and the prospects for the future.

Keywords: under-ground experiments, under-water experiments, under-ice experiments, neutrino telescopes, dark matter

1. Introduction

Astroparticle experiments have provided richful physics results for many years. In this conference have seen many examples of the most recent advances and the prospects for the future, showing that this yield is growing and will continue giving us answers (and new questions) during the the following years.

In this paper I will report on the results presented which are related with one three following topics: dark matter, under-ground experiments and neutrinos.

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2. Dark matter

Evidence for dark matter has been accumulating for almost one century [1]. The experimental hints for its existence include galaxy clusters, the rotation curves of galaxies, structure formation, filaments, the Bullet cluster, etc. The main ingredient of the Universe is dark energy. From the last results of Planck satellite, the dark energy content has been estimated in 68.3%. Dark matter contribution is 26.8% and ordinary matter is just 4.9% of the total. In other words, approximately 85% of the matter in the Universe is dark matter. The basic requirements for a good dark matter candidate are to be stable (or very long-lived), neutral and with an interaction cross section of the order of the one of the weak interaction. The only viable candidate within the Standard Model would be the neutrino, but since neutrinos are relativistic, they cannot explain the structure formation of the Universe. Therefore, the explanation for dark matter has to be outside the Standard Model.

The question of identifying the nature of dark matter has to be approached from several experimental fronts at the same time. For instance, there are many searches for supersymmetric partners of the Standard Model particles at the Large Hadron Collider. These experiments have succeeded in finding what looks very much like the Higgs boson, but for the moment, only limits on models beyond the Standard Model, like Supersymmetry, have been set (see Figure 1 for an example). In the mean time, these results are weakening the arguments in favor of naturalness [2]. As an example of model to explain the experimental results, M. Peiró [3] proposes an extension of the Next-to-MSSM (NMSSM) with right-handed neutrinos, in which the right-handed component of sneutrinos can be a good DM candidate. The coupling of these sneutrinos with the Higgs is of the order of the electroweak scale, making possible the thermal production of these particles. There is a wide range of predictions for both direct and indirect detection of DM experiments for very light sneutrinos. The different predictions are related, generally, with the final state annihilation in the early universe of these light particles.

In any case, a positive signal at LHC will not be enough to claim the discovery of dark matter, since one of the main features that a dark matter candidate has to fulfill, the stability at cosmological scales, cannot be proven in accelerators. The other two fronts which complement this task are the so-called direct and indirect searches. In the first case, the interaction of dark

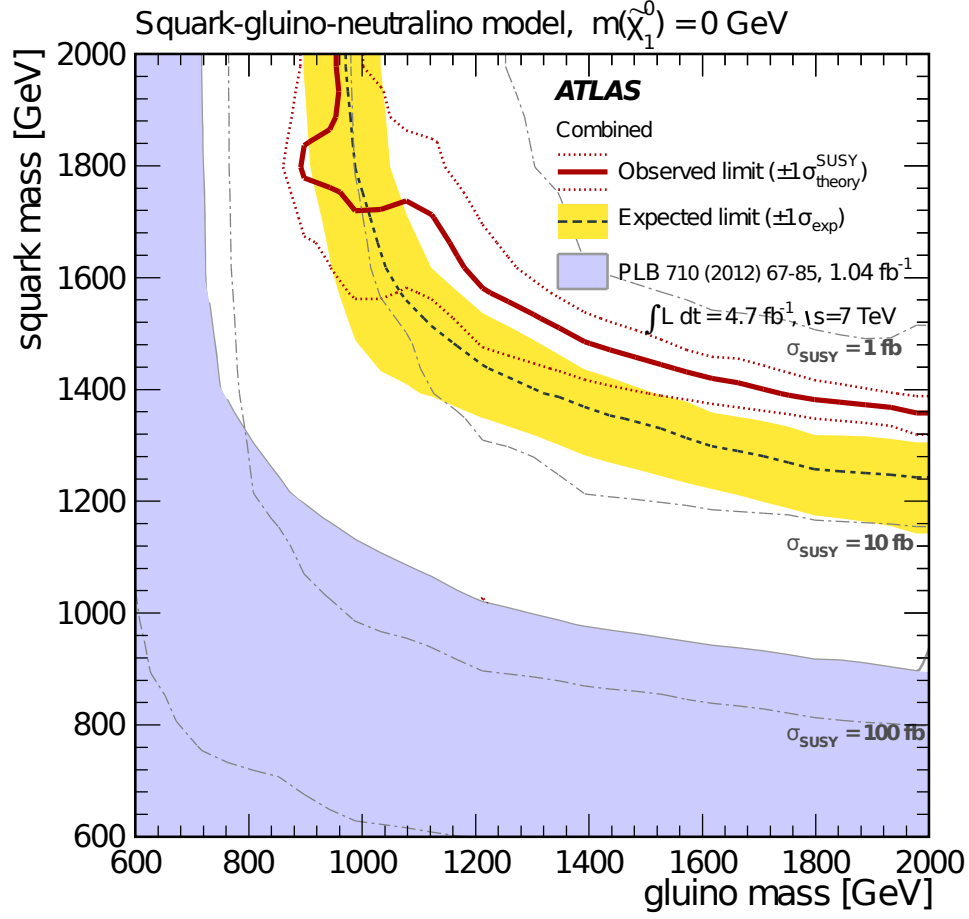


Figure 1: Example of constraints to CMSSM from LCH results.

matter particles in the detector are looked for. The experimental effort here is very broad. Three main signatures are used, often combined in pairs in order to improve the sensitivity: scillation (light), ionization (charge) and phonon (heat). Another technique which is being tested are the superheated liquids (bubbles). Figure 2 shows a summary of present and future experiments, indicating the techniques used in each case. The present situation is quite puzzling and very interesting. There are positive results (DAMA/LIBRA, COGENT, CRESST, CDMS-Si) which are in contradiction, at least for the most simple assumptions, with limits set by other experiments (XENON100,

CDMS-Ge). Moreover, the signal regions of the positive results are at least in tension among themselves. In the following subsections we review some of these experiments.

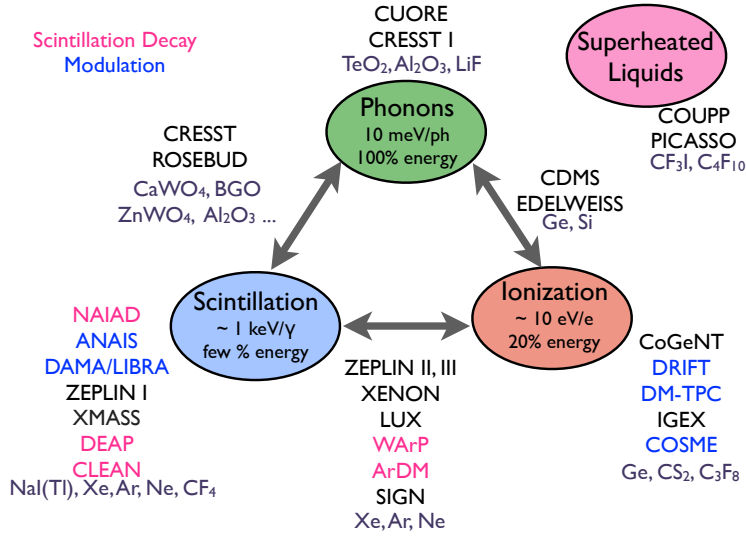


Figure 2: Experimental approaches for direct dark matter detection. The figure includes both present and future experiments. (Form C. Cuesta thesis defense).

Indirect searches look for the particles resulting from the decay or annihilation of dark matter particles. This includes photons, cosmic rays and neutrinos. For a summary of the results presented in this conference for photons and cosmic rays, see [4] [5]. As described there, there are several hints which could be compatible with dark matter. However, there are also more standard astrophysical scenarios which could explain these results. Searches for WIMPs in the Sun by neutrino telescopes would not have this problem if a signal is detected, since no astrophysical explanation would compete. In this proceeding we will review the results of the ANTARES neutrino telescope.

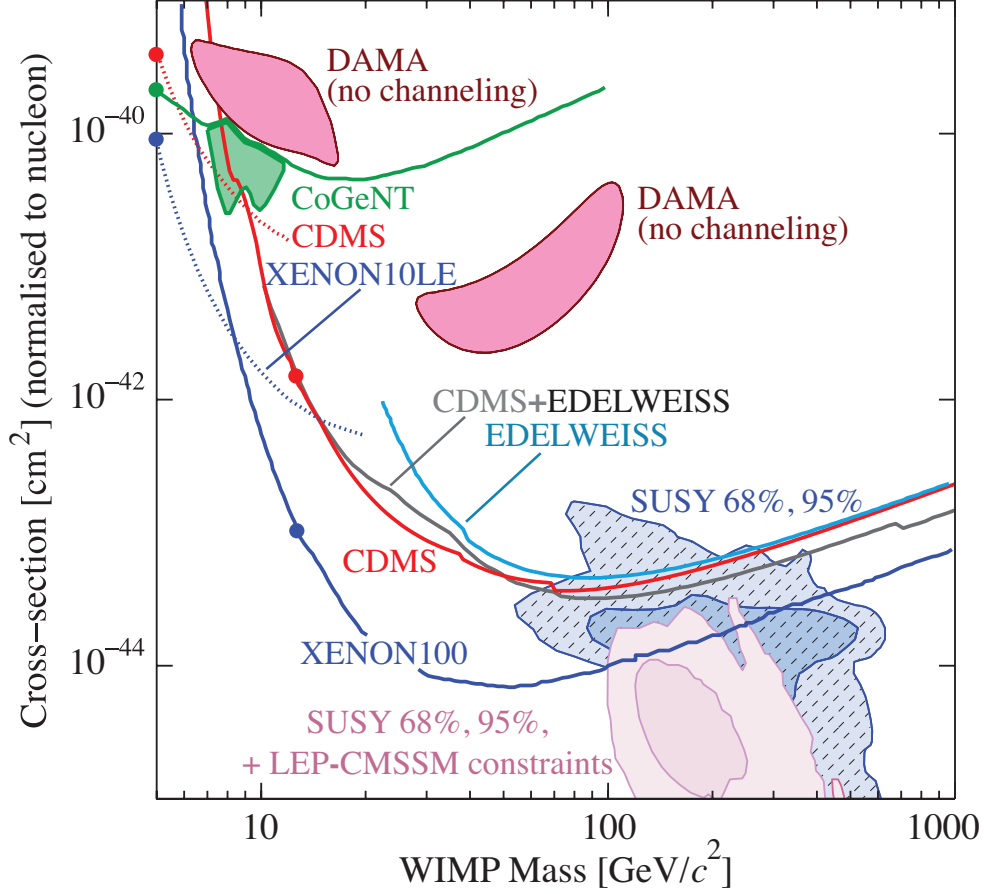


Figure 3: Experimental limits and signal favoured regions obtained from the results of different direct searches of dark matter (source: Particle Data Group.)

2.1. DAMA/Libra

The DAMA/LIBRA collaboration [6] has deployed about 250 kg of highly radiopure NaI(Tl) at the Gran Sasso National Laboratory. They have observed an annual modulation signature which is compatible with the assumption that it is produced by the asymmetry in the expected rates of dark matter particle interactions when the Earth is moving forward or backwards the "wind" of dark matter seen as the Sun moves around the Galaxy. The requirements for such a signal in this scenario are that it has to be modulated according to a cosine function, in a definite low energy range, with a

period of one year, whose maximum should be at June 2nd and to be observed just for single hit events in a multi-detector set-up. The significance of the observed signal after a total exposure of $1.17 \text{ tons} \times \text{year}$ is 8.9σ . The collaboration has made a lot of effort to discard many possible systematic effects which could produce a spurious signal, with negative results: none of the investigated process is able to simultaneously satisfy all the peculiarities of the signature. The collaboration plans to continue data taking with a new configuration which would lower the energy threshold below 2 keV.

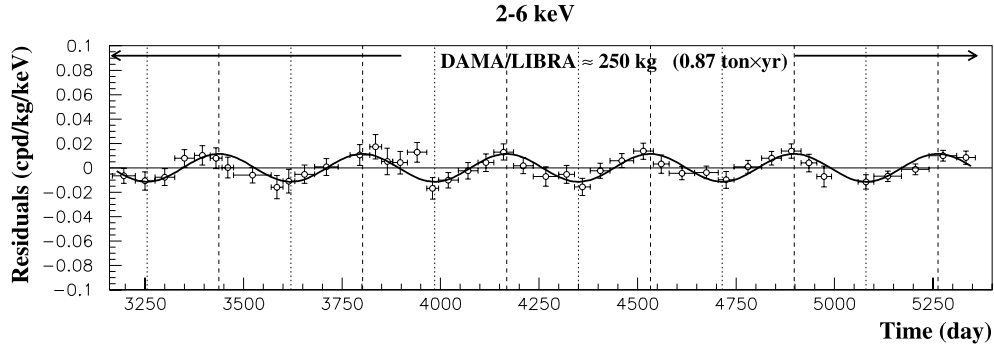


Figure 4: Annual modulation (residual rate of single-hit scillation events) observed by the DAMA/LIBRA experiment in the 2-6 keV interval.

2.2. ANAIS

The ANAIS project [7] aims to set up a 250 kg potassium-purified NaI(Tl) detector in the Canfranc Underground Laboratory. The goal is to confirm the annual modulation observed by the DAMA/LIBRA experiment. The target mass will be divided in 20 modules containing of a 12.5 kg cristal coupled to two photomultipliers. A first test module (ANAIS-0, 9.6 kg) was characterized at the Canfranc Laboratory. These measurements allowed, among other things, to optimize the event selection strategy, to design the calibration method and to test the acquisition code and electronics. Also several photomultiplier models were tested. From December 2012, measurements on two 12.5 kg modules (ANAIS-D0 and ANAIS-D1) have been performed to determine the bulk contamination. The potassium-40 bulk content has been measured as 41.7 ± 3.7 ppb, by performing a search for coincidences of 3.2 keV in one detector and 1460.9 keV in the other (see Figure 5). Concerning the ^{232}Th and ^{238}U chains, a high rate (3.15 mBq/kg) have been observed,

attributable to ^{238}U chain with broken equilibrium. The contribution from cosmogenic activated isotopes can also be clearly identified and its decay along the first months of data taking is observed. A background model is under development to reproduce the observed rates.

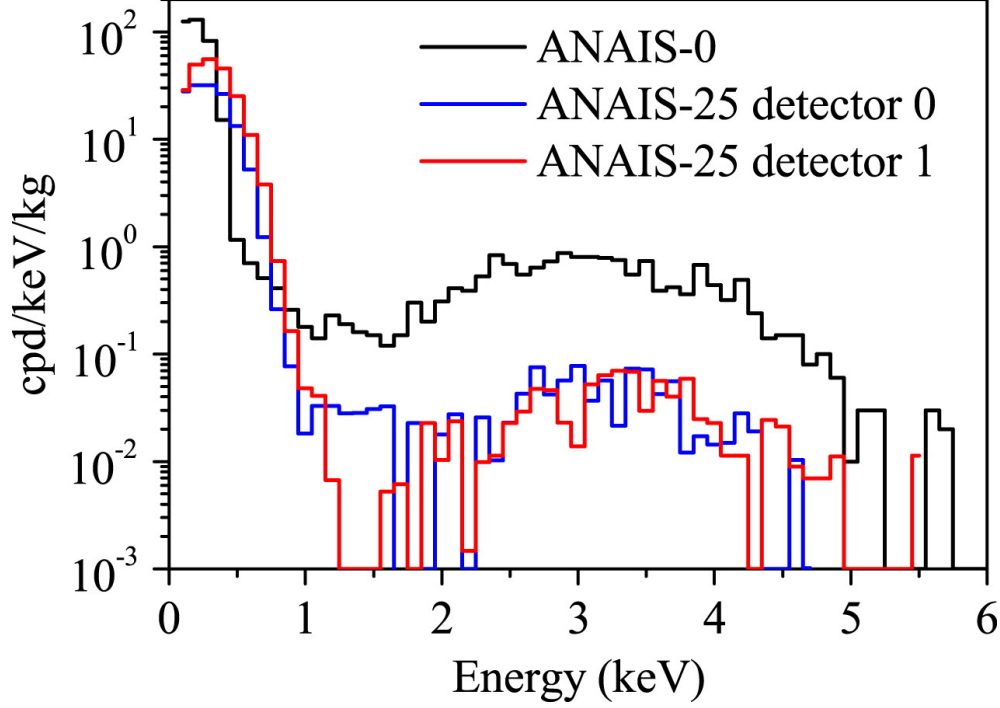


Figure 5: Background of potassium-40 as measured for the ANAIS-0 test module (9.6 kg) and the ANAIS-D0 and ANAIS-D1 modules (12.5 kg each).

2.3. *DarkSide*

The DarkSide-50 detector [8] is a two phase Argon TPC intalled in the the Gran Sasso Laboratory. The experimental design follows a null background strategy, so that an unambiguous discovery could be claimed with just a few WIMP candidates. To this end, several strategies are implemented, apart from setting the detector deep underground. First, to reject electro/gamma background by using the information on the shape of the scillation signal, the ratio between ionization and scintillation and the 3D location of the event. Second, to use underground argon depleted in ^{39}Ar , which is 150 times more

radiopure than atmospheric argon. Third, to use a liquid scintillator as active neutron veto. Fourth, to use a water tank for detection of muons and shielding against external neutrons. The total expected background with this setup is less than 0.1 per ton and year. As a first step to estimate the background and validate the setup, a smaller version has been built (DarkSide-10, 10 kg target), which has been successfully operated for one year. The DarkSide-50 detector (50 kg target) is under commissioning and the expected sensitivity is indicated in Figure 6, compared with other experimental results.

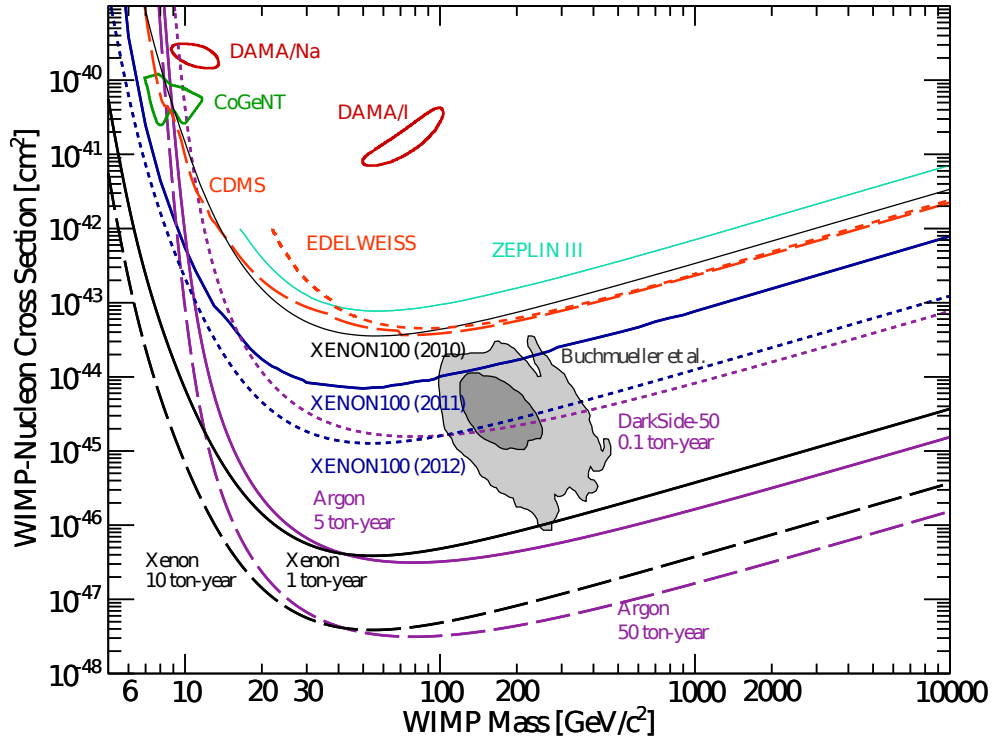


Figure 6: Expected sensitivity for DarkSide-50 to the WIMP-nucleon scattering cross section, compared to other experiments.

2.4. ANTARES

The ANTARES neutrino telescope is a three-dimensional array of 885 photomultipliers installed in the Mediterranean sea (more details in 4.2). In addition to the detection of neutrinos of astrophysical origin, the indirect

detection of dark matter is a major scientific goal of the experiment. The idea is that WIMPs would accumulate in massive objects like the Sun and their annihilation would produce (directly or indirectly) high energy neutrinos. One of the advantages of such kind of detectors is that a potential signal from the Sun would be a very clean indication of dark matter, since no other astrophysical explanations are envisaged, contrary to the situation of other indirect searches (like positrons or gammas) for which the rejection of astrophysical sources is much more difficult (i.e. pulsars in the case of positrons). ANTARES has already produced limits for neutralinos in the Sun with data taken during 2007-08 [9] (a new analysis with 2007-2012 data is also about to be completed, as well another one looking for a signal in the Galactic Center). The analysis is a binned search in which the search cone has been optimized for optimum sensitivity. The signal is simulated with the WimpSim package and the background is directly obtained by scrambling data, which has the advantage of lower systematic uncertainties. There are two sources of background. On the one hand, the muons produced by cosmic rays in the atmosphere, which can be greatly rejected by selecting only upgoing events. Still, an important number of atmospheric muons which are misreconstructed as upgoing remain, so further cuts on the quality of the reconstructed track are needed. A second source of background are the atmospheric neutrinos, also produced by cosmic rays in the atmosphere. This is an irreducible background, but distributed smoothly in the sky, contrary to a potential signal, which should concentrate in the Sun's direction. Figure 7 shows the limits on the spin dependent WIMP-proton cross section. For this case, the limits are better than those obtained by direct search experiments.

3. Underground experiments

The background produced by cosmic rays (in particular atmospheric atmospheric muons since they are the most penetrating component) makes impossible to carry out experiments of low signal on the surface. This is way it is important to shield the detectors by installing them deep underground. In order to reduce costs, the location is typically in already made excavated sites, like old mines or tunnels through mountains. This is the case of some of the experiments looking for dark matter presented in the previous section and also the ones presented in this section (those non related with dark matter), all of them installed in the Gran Sasso Laboratory.

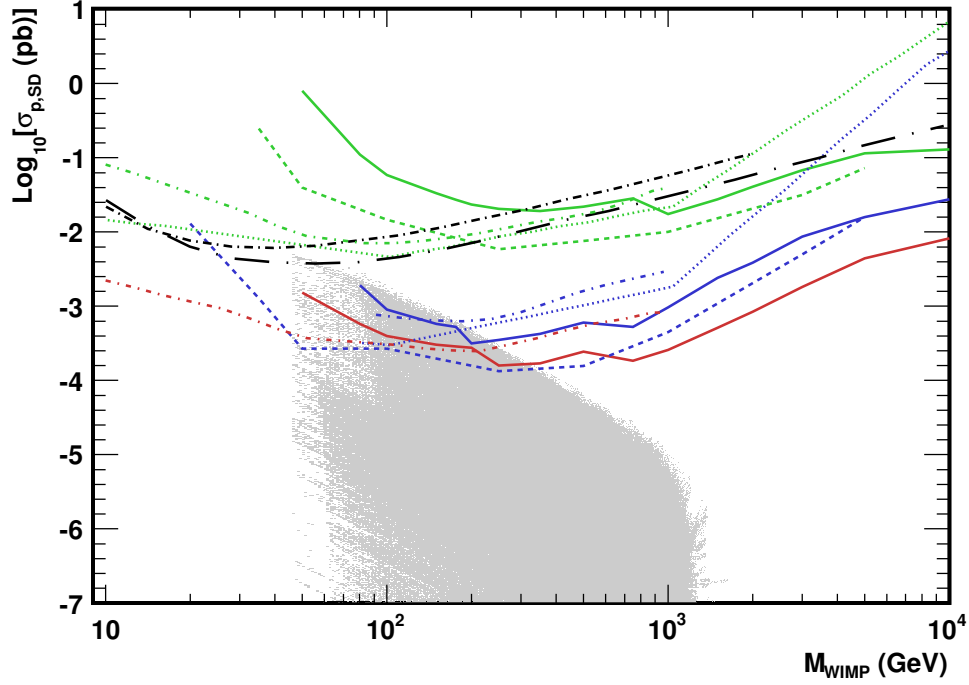


Figure 7: 90% CL upper limits on the SD WIMP-proton cross-sections (plots on the left and right, respectively) as a function of the WIMP mass, for the three self-annihilation channels: $b\bar{b}$ (green), W^+W^- (blue) and $\tau^+\tau^-$ (red), for ANTARES 2007-2008 (solid line) compared to the results of other indirect search experiments: Baksan 1978 – 2009 (dash-dotted lines), Super-Kamiokande 1996 – 2008 (dotted lines) and IceCube-79 2010 – 2011 (dashed lines) and the result of the most stringent direct search experiments (black): SIMPLE 2004 – 2011 (short dot-dashed line in upper plot), COUPP 2010 – 2011 (long dot-dashed line in upper plot) and XENON100 2011 – 2012 (dashed line in lower plot). The results of a grid scan of CMSSM-7 is included (grey shaded area) for the sake of comparison.

3.1. Borexino

The Borexino experiment [10] is a low background neutrino detector located at Gran Sasso Laboratory whose main goal is the detection of sub-MeV solar neutrinos. The signature for this search is neutrino electron scattering produced in a nylon vessel containing 278 tons of organic liquid scintillator. This vessel is surrounded itself by a water tank for gamma and neutron shielding. One of the most relevant and recent results from Borexino is the first detection of pep solar neutrinos. This measurement is important because

it offers a more stringent test on oscillation models. Another recent result is the strongest constraint on the CNO solar neutrino flux, which is key in order to distinguish between high and low metallicity models. In order to make possible these analyses and given the involved fluxes (ten times lower than those for ${}^7\text{Be}$, it is crucial to reject the cosmogenic ${}^{11}\text{C}$, which is the dominant background in the 1-2 MeV range. This is done by a threefold coincidence technique and pulse shape discrimination. In addition to solar neutrinos, the scientific program of Borexino also includes geoneutrinos (antineutrinos emitted in beta decays of naturally occurring radioactive isotopes in the Earth's crust and mantle). The location of Borexino offers the advantage of a moderate contamination from nuclear reactors. Values for the fluxes from Uranium and Thorium have been obtained.

3.2. GERDA

The main goal of the GERDA experiment [11], located in the Gran Sasso Laboratory, is the detection of neutrinoless double beta decay in ${}^{76}\text{Ge}$, which would prove the Majorana nature of neutrinos. The detector uses isotopically enriched Ge diode embedded directly in liquid Argon, which serves for cooling, radiation shielding and active veto. The Phase I of the experiment has used ~ 18 kg of enriched Germanium, taking data in the period November 2012 - May 2013, with a total exposure of 20.9 kg year for the enriched detectors. For the Phase II, to start in 2013, 30 additional enriched BEGe (Broad Energy Germanium) detectors will be added, for a total of 48 kg of enriched Germanium. For this phase, the goal is to have background at the level of a few counts/(keV kg yr), with a total exposure of >100 kg year and a liquid Argon scintillation veto. The detector includes a muon Cherenkov veto, a detector anti-coincidence veto, a pulse shape discrimination. In Figure 9 the energy spectrum after selection cuts is shown. Several background components can be identified, like ${}^{39}\text{Ar}$, ${}^{42}\text{K}$, gamma lines and the surface alphas. The collaboration has followed a blinding strategy for the data, in order to avoid selection biases. The region in ± 20 keV around $Q_{\beta\beta}$ will be soon unblinded.

3.3. LUNA

The 400 kV LUNA accelerator [12] is located in the Gran Sasso Laboratory and provides beams of protons, ${}^4\text{He}$ and ${}^3\text{He}$. This accelerator allows to measure nuclear cross-sections which are important to understand several astrophysical phenomena like nucleosynthesis, energy production in stars or

stellar evolution models. Direct measurements of cross-sections are important in order to avoid problems from extrapolations from higher energies due to resonances. One example of recent result obtained with LUNA is the measurement of resonance strengths $\omega\gamma$ in the reaction $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$. The obtained results imply a reduction of the estimated contribution of Wolf-Rayet stars to the galactic production of ^{26}Al .

4. Neutrino telescopes

Neutrino astronomy has become an important tool both for astrophysics and particle physics. In order to study the Universe at high energies, traditional probes like photons and protons have important drawbacks. High energy photons interact with matter and radiation, which limits their range. Protons can be also absorbed by radiation and matter. Moreover, protons, being charged particles, are deflected by magnetic fields, which erases the directional information. This is why, more than one hundred years after the discovery of the extraterrestrial origin of cosmic rays, their sources are still unknown, in particular at high energies. Neutrinos, on the other hand, are neutral and only interact weakly. The price to pay is that large detector volumes are needed given the weak cross section and fluxes involved. In any case, gamma astronomy, cosmic rays and neutrinos are closely related. In processes where cosmic rays are expected to be produced (via interaction of those with matter or radiation, yielding pions) gamma rays and neutrinos are also expected, from the decay of the neutral and charged pions respectively. Therefore, the main goals of neutrino telescopes is the understanding the origin of cosmic rays (since neutrinos are also produced and they point back to the sources) and disentangle between the hadronic (where neutrinos are also produced) or leptonic (no neutrino production) mechanisms which can explain the gamma rays observed from several astrophysical sources. Another important motivation is to look for dark matter from sources like the Sun, as explained before. There are two main signatures in neutrino telescopes. First the long tracks observed by the array of photomultipliers of the Cherenkov photons induced by the relativistic muons produced in the CC interactions of neutrinos around/inside the detector. The second signature correspond to CC interactions of electron and tau neutrinos as well as the NC interactions of any flavour, where a shower is produced and observed as a bright sphere of light. Given the large volumes of transparent media required for such detectors, two options arise: the Antarctic ice or lakes/sea water. For very high

energies, i.e. above tens of PeV a different strategy has to be followed, since the fluxes are too low and require larger detection volumes. To instrument such large volumes with photodetectors would be too expensive, given the attenuation length of light. Therefore, acoustic or radio signals have to be used. An analysis on how to discriminate between different neutrino flavors in radio neutrino experiments can be found here [13].

In the following, we review the status and some results of the water Cherenkov neutrino telescopes in the world.

4.1. IceCube

The IceCube detector is installed in deep ice in the Antarctic. It consists of 5160 photomultipliers distributed along 86 lines deployed at a depth between 2.5 and 1.5 km under the surface. There is also a complementary array of water Cherenkov tanks on the surface, IceTop, with a total of 324 photomultipliers. The detector was completed in 2011, although data taking was possible with only part of the detector deployed, producing a rich set of physics results. For instance, the observations when only 40 lines of IceCube were operative (IC40) produced a set of limits in the neutrino flux for a list of blazars that had been observed by Fermi. Assuming that the flux of photons are produced by hadronic mechanisms, limits on the primary proton flux can be set [14]. An example of the limits obtained for 3C273, for the case of $p\text{-}\gamma$ interaction and for the accretion disk spectrum model is shown in Figure 11.

The data of 2011-2012, when the IceCube detector was almost finished (IC79) or already completed (IC86), has produced a result which seems to be the first evidence of extraterrestrial neutrinos [15]. The first hint came from the observation of cascade events with reconstructed energies just above 1 PeV. These two events were found when looking for cosmogenic neutrinos, but their energies are too low to be compatible with such origin. On the other hand, this suggested to lower the energy threshold to look for more events in the 100 TeV - 1 PeV region. The event selection strategy was based on looking for High-Energy Starting Events (HESE), i.e. events for which the interaction vertex is contained inside the detector. In order to make such a selection, the external lines of the detector are used for vetoing, ensuring that the deposition of energy starts inside the detector. The advantage of this strategy is that the background is greatly reduced both down-going atmospheric muons and atmospheric neutrinos (which are usually accompanied by muons produced in the cosmic ray showers producing them). This allows the acceptance of the detector to cover homogeneously the whole sky. The energy

threshold, contrary to previous analysis looking for downward events, where it was \sim PeV, it is about 80 TeV. The expected background for the period of the analysis (May 2010 - May 2012) is 6.0 ± 3.4 atmospheric muons and $6.1^{+3.4}_{-3.9}$ atmospheric neutrinos (including conventional and prompt contributions). The total background is therefore $12^{+4.5}_{-3.9}$. The number of observed events is 28, including the two PeV events already observed in the previous analysis (see Figure 12). The total significance (without including the two previous PeV events) is 4.3σ . In addition to the rate, there are other hints which support the extraterrestrial origin of this excess. Out of the 28 events, 21 of them are cascades and 7 are tracks. This is compatible with the cosmic origin (when the effect of oscillation is taken into account) but not with the conventional atmospheric neutrino expectations. The spectrum is consistent with a E^{-2} index (with a cutoff about 1.6 PeV). This is a factor two below the previous limits of IceCube for the standard diffuse flux analysis. Moreover, the vertices are homogenously distributed within the detector, disfavouring a possible leak of atmospheric origin.

Concerning the distribution of the events in the sky, there is an excess from the Southern hemisphere 13. Part of this excess is expected due to the absorption on Earth for upgoing (Northern origin) events. There is still an intriguing excess when the previous effect is taken into account, although not very significant, so the measured declinations seem to be compatible with a diffuse distribution.

4.2. ANTARES

The ANTARES detector [16] is located 2500 m deep in the Mediterranean Sea, at 40 km of the French city of Toulon. This location offers a great visibility of the Galactic Center and most of the Galactic Plane. It consists of 885 photomultipliers distributed along 12 vertical anchored at the sea bed and kept vertical by a buoy. The detector was completed in 2008. The scientific output has been very rich, including search for point sources, cosmic diffuse fluxes, first oscillation effects observed by a neutrino telescopes, search for correlations with transient sources like gamma ray bursts, blazars and microquasars and with gravitational waves and also searches for more exotic physics like monopoles or nuclearites. In the following we review a few of these results. Figure 14 shows the result of the all-sky search for point-like neutrino sources, using 2007-2010 data (813 active days). The most significant cluster is indicated by the circle (centered at $\delta = -46.5^\circ$ and R.A. = -65.0°). The post-trial significance is 2.2σ . In parallel to this all-sky analysis,

a search in specific locations of good neutrino candidates sources has been made, without any relevant excess.

For sources which are transient [17] (both single-event cases like gamma-ray bursts and flaring sources like AGNs or micro-quasars), the information about when the neutrinos are expected allows to reduce greatly the background and improve the sensitivity, as shown in Figure 15. Several searches have been carried out in ANTARES following this strategy, including 287 gamma-ray bursts occurring during 2008-2011, 10 flaring blazars from the 2008 Fermi catalogue and 8 micro-quasars flaring during 2007-2010. A coincidence was observed (0.56°) with a flare of the blazar 3C279, which gives a post trial p-value of 0.1. No other coincidences has been observed.

Another interesting analysis using the idea of correlations to increase sensitivity concerns the search for gravitational waves in coincidence with high energy neutrino events [18]. 216 neutrino triggers in the data of 2007 have been analyzed with gravitational wave data of the LIGO and VIRGO experiments. One event had a false alarm probability of 0.004, which is perfectly compatible with background when the number of trials is taken into account. Assuming some assumptions in the gravitational wave generation, exclusion distances can be set, as shown in Figure 16.

4.3. *KM3NeT*

The KM3NeT project [19] is the joint effort of the ANTARES, NEMO and NESTOR collaborations to build a multi-km³ detector in the Mediterranean Sea. There has been an extensive program of R&D for the design of the detector and the associated technologies (deployment of lines, etc.) One of the novelties fruit from this R&D program is the multi-PMT optical module: instead of a large photocathode area PMT, the optical modules will contain 31 3" PMTs, which offers an increased total photocathode area, a better 1-vs-2 photoelectron separation and directionality information.

Among the recent progress made by the collaboration for testing the elements of the detector, we can mention the mounting of one multi-PMT optical module in the so-called Instrumentation Line of ANTARES, installed in April 2013 at the ANTARES site. The multi-PMT optical module is fully operational and working correctly (see Figure 17). Moreover, a test for the deployment and unfurling of a prototype KM3NeT line was successfully carried out in April 2013.

4.4. *NEMO*

The NEMO collaboration [20] has carried a R&D program to develop a cubic kilometer detector close to Capo Passero (Sicily). In the so-called NEMO Phase II Project, the Capo Passero site has been evaluated and a tower prototype has been successfully installed in March 2013. This tower contains eight bars (8 m long) with a vertical separation of 40 m and 4 PMTs in each bar. Moreover, it contains several calibration instruments, including hydrophones for positioning and a laser beacon and a LED beacon, used for time calibration. The data taking is going-on smoothly. The KM3Net-Italy project is developing the communication architecture and new electronics for KM3NeT.

4.5. *Baikal-GVD*

The GVD project [21] is the extension of the Baikal detector, installed in the Baikal lake in Siberia. The Baikal neutrino telescope pioneered neutrino astronomy. One of the advantages of the site is the freezing of the lake surface during winter, which allows to install and test equipment and to make all the connections on dry. The GVD extension would consist of $\sim 10,000$ additional PMTs installed in 216 strings. The active part of the detector would be installed at depths between 600 and 1300 m. The total instrumented volume would be 1.5 km^3 . Several prototype lines have already been installed and tested. In 2012, a cluster with 3 full-scale lines (with 24 PMTs) was installed and taking data since April 2012. In 2013, 3 full-scale strings (72 PMTs), with updated electronics, were installed and are taking data since April 2013. The next goal is to install by 2015 eight full scale lines.

5. Conclusions

There are many frontier physics topics for which it is necessary to be protected from the atmospheric muon cosmic ray background and therefore to install detectors deep under-ground, under-sea or under-ice. These hot topics include the search for dark matter, the Majorana nature of neutrinos, the solar neutrinos or other astrophysical neutrino sources. We have seen in this conference important advances in several of these topics. In dark matter searches, for instance, we are in the very thrilling situation in which there are hints of first detection together with exclusion limits which in their simplest interpretation seem incompatible with such signals. In the mean time, we are likely attending the dawn of the neutrino astronomy. The events observed by

IceCube are very difficult to explain from the background due to atmospheric muon and neutrinos, not only for the observed rates at high energies, but also for the ratio between showers and tracks, the observed spectral index or the distribution of the vertices in the detector. This first evidence of cosmic neutrinos should be confirmed by more data from IceCube and by the future detectors like KM3NeT and Baikal-GVD, already successfully deploying the first prototype lines. In parallel, we have also seen the potential of the multi-messenger approach, which allow to increase the sensitivity using the information of other channels like gamma rays or gravitational waves. Next years will provide us many more information (and probably puzzles) with all the data we will gather under the surface.

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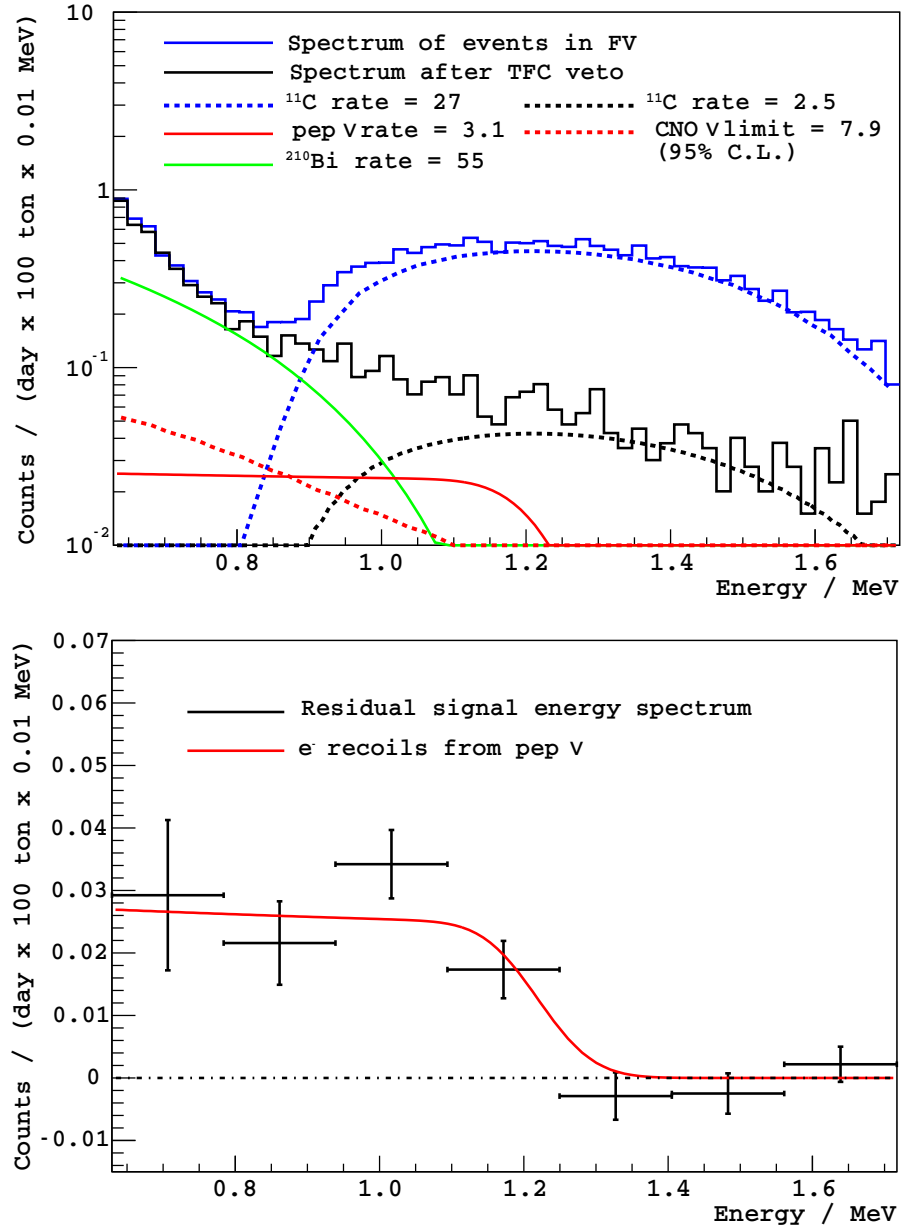


Figure 8: Top: Energy spectrum obtained in the Borexino detector for the search of e^{-} recoils from pep neutrinos. The plot shows both the spectrum before and after applying a triple coincidence cut used for reducing the ^{11}C background. Bottom: Residual spectrum after subtracting the background.

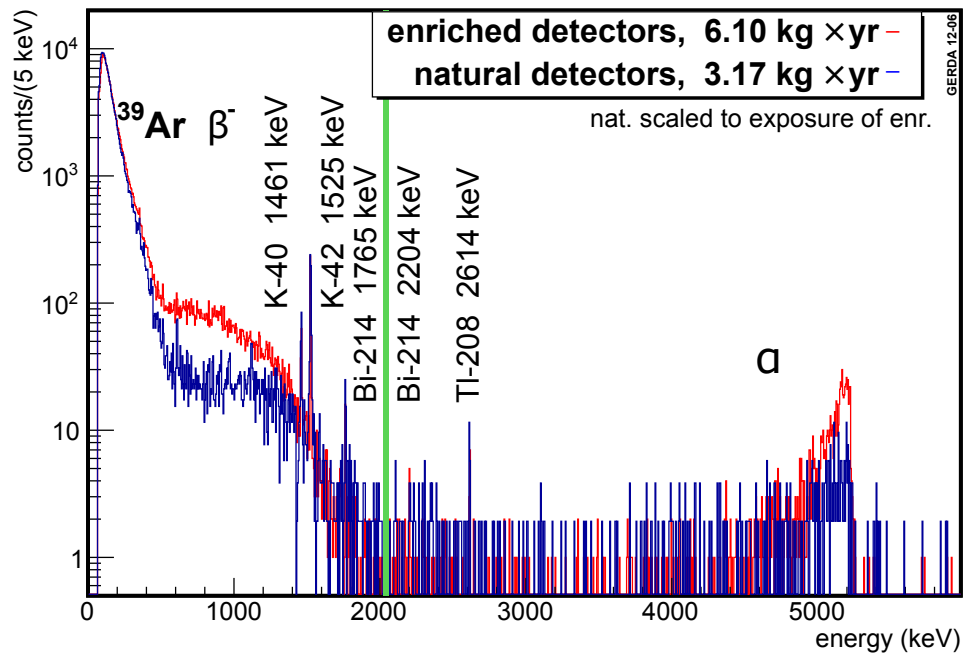
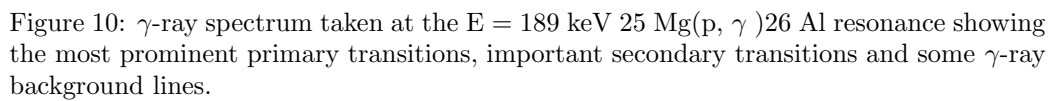


Figure 9: Spectrum of enriched (red) and natural (blue) diodes for the GERDA experiment. The region ± 20 keV around $Q_{\beta\beta}$ is blinded, as indicated in green in the figure.



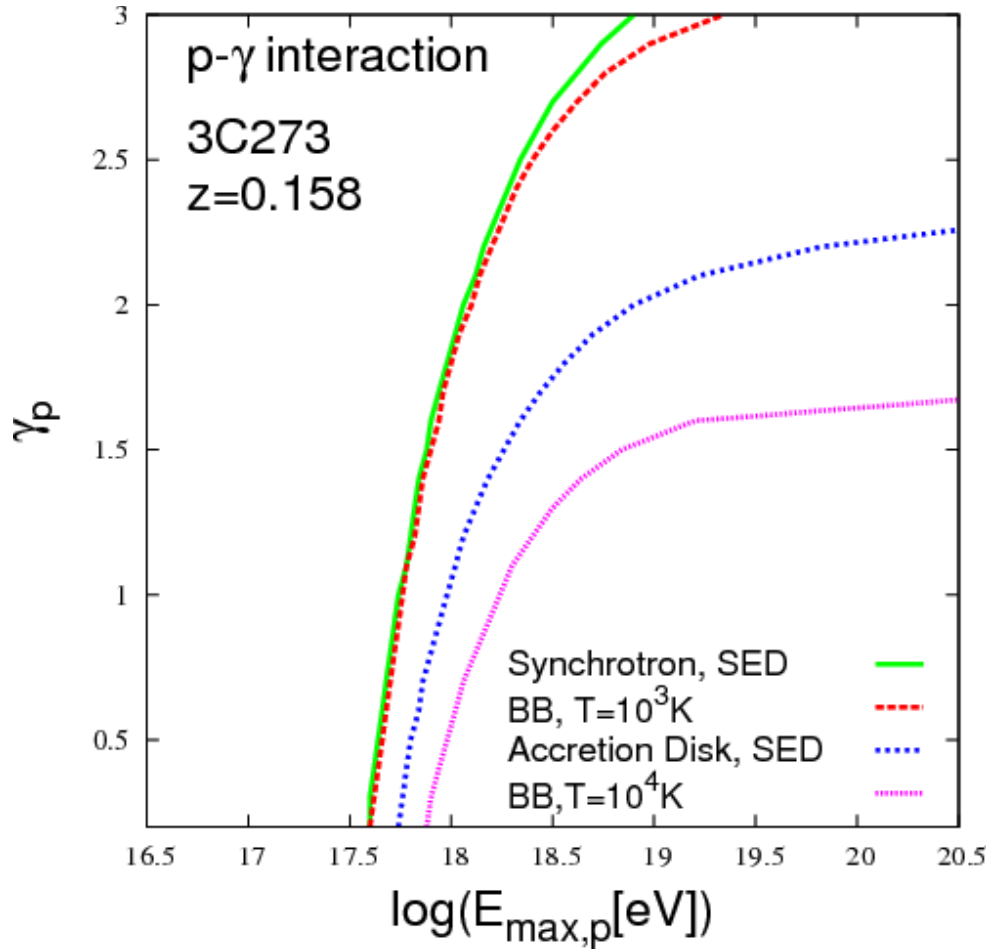


Figure 11: Constraints on $(E_{\max,p}, \gamma_p)$ deduced in the $p\gamma$ model for proton interactions with a soft photon distribution corresponding to the accretion disk spectrum [14].

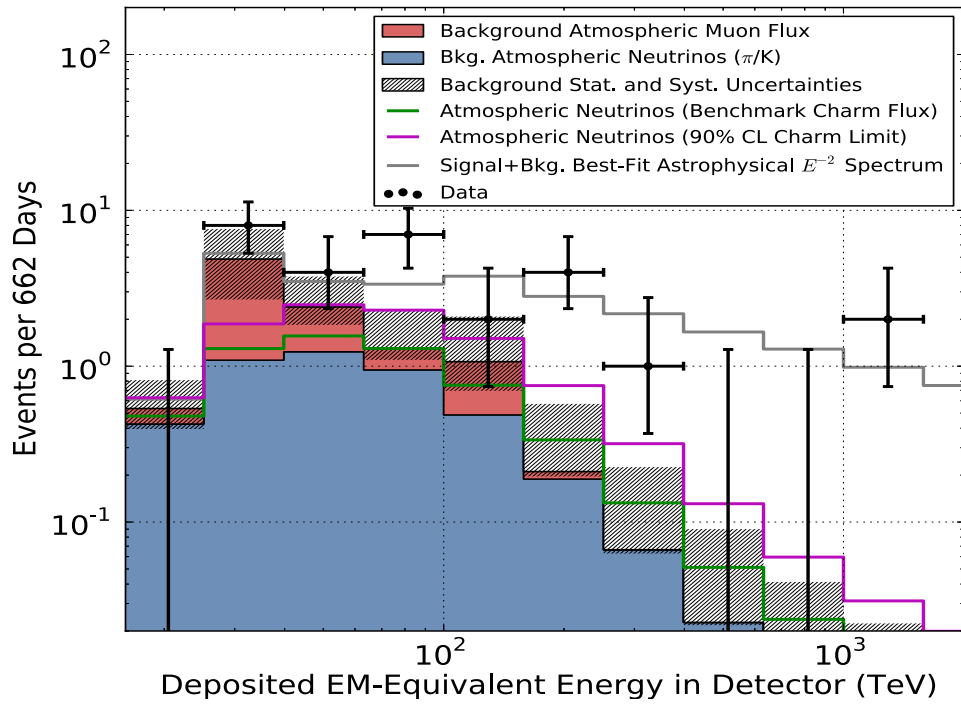


Figure 12: Distribution of deposited energy in the IceCube detector for the HESE analysis.

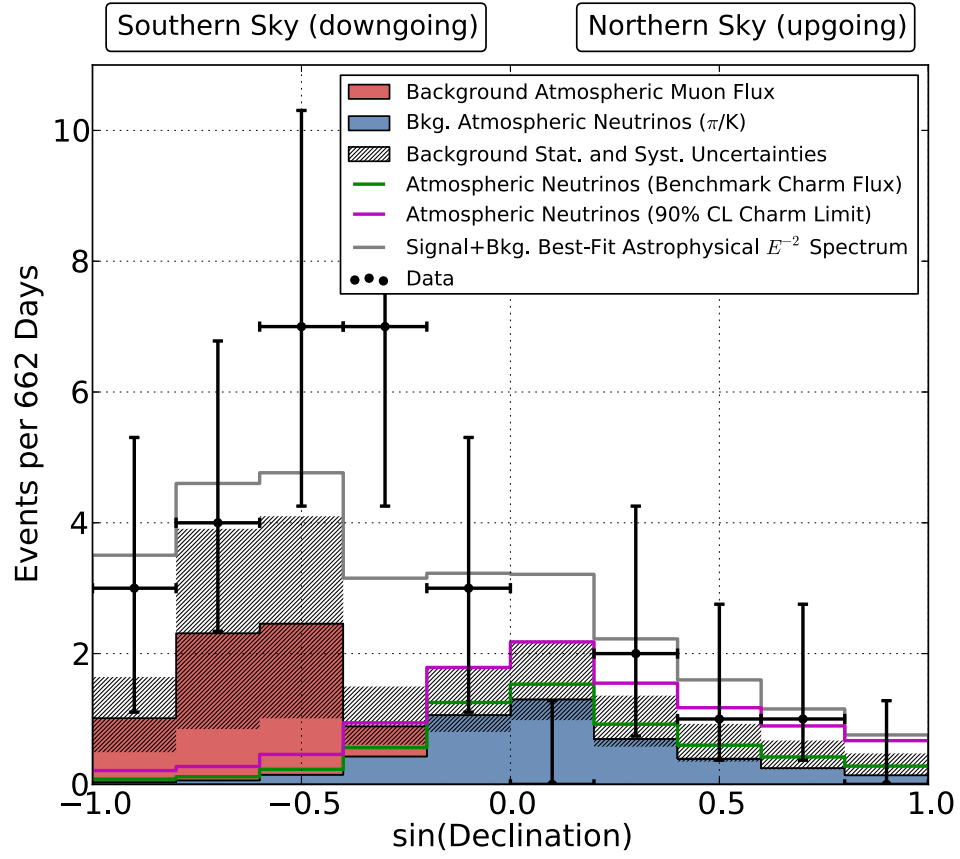


Figure 13: Declination distribution of the 28 events observed by IceCube in the HESE analysis.

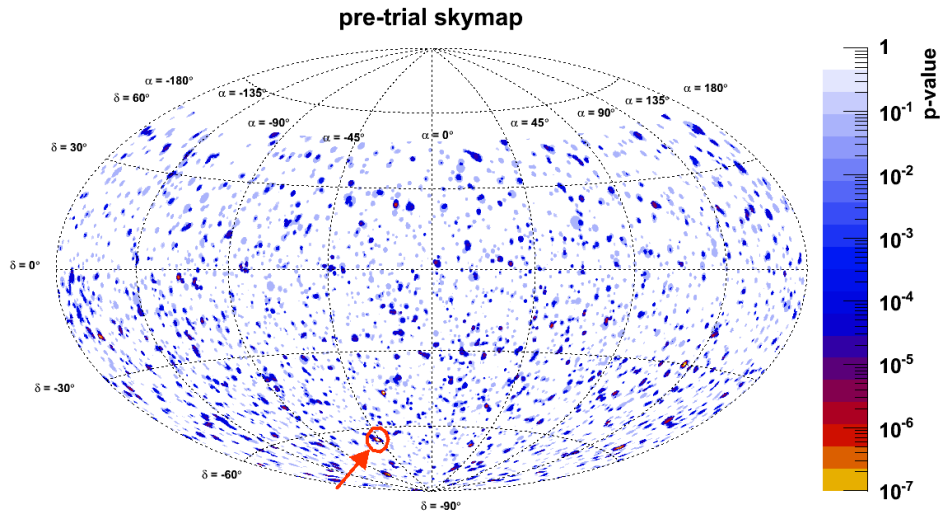


Figure 14: Skymap in equatorial coordinates of the pre-trial p-values observed by ANTARES.

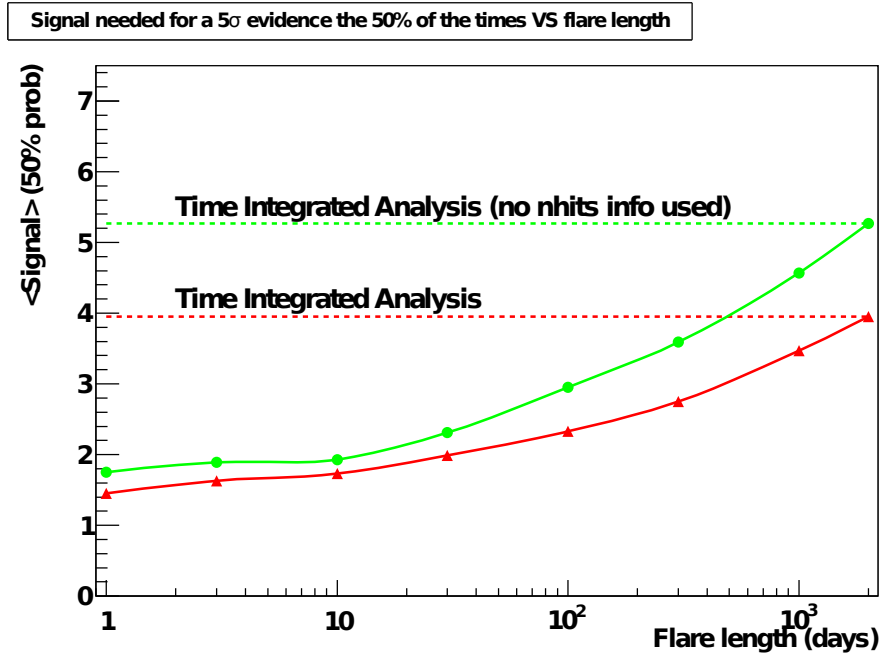


Figure 15: Number of events needed for a 5σ discovery (for a source at $\delta=-40^\circ$) when the time information is used for transient sources (solid line) compared to the case of not using the timing information (dashed line), computed using (red) or not (green) the energy information in the likelihood.

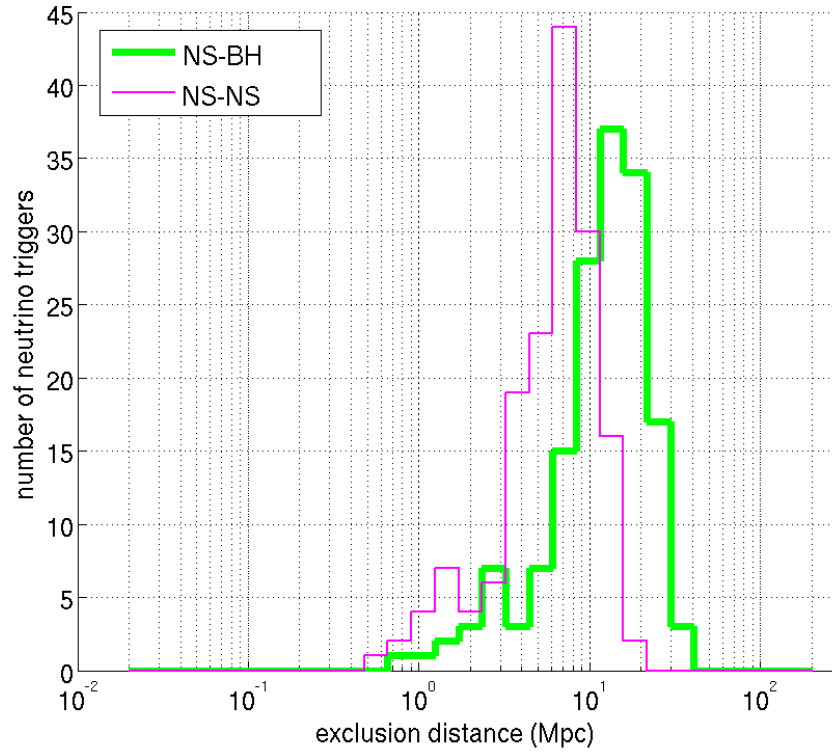


Figure 16: Distance exclusions for two potential scenarios for gravitational waves and high energy neutrinos joint production: Neutron Star - Black Hole (NS-BH) and Neutron Star - Neutron Star (NS-NS).

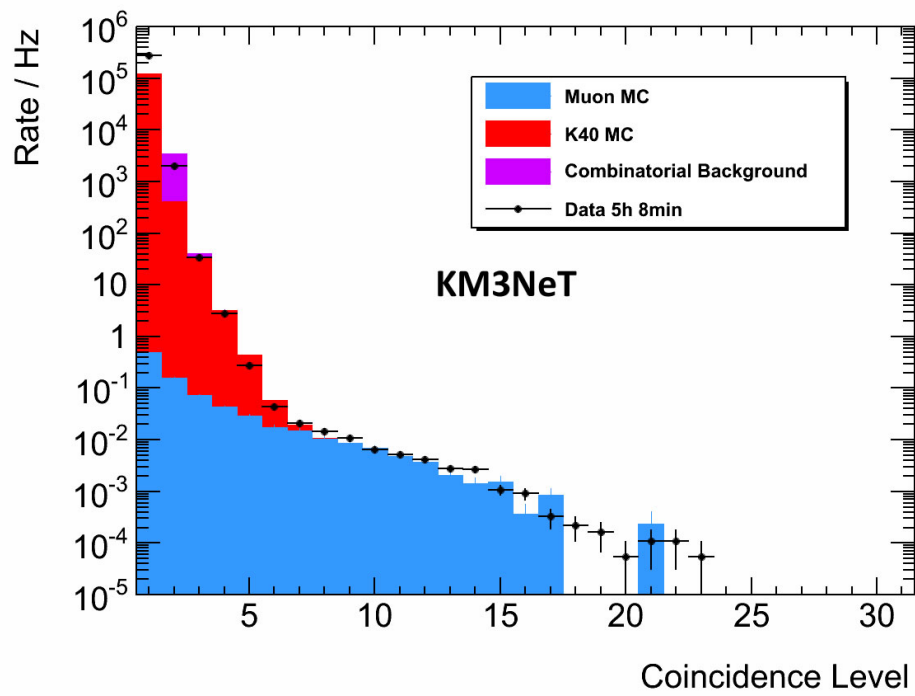


Figure 17: Coincidence rates for the KM3NeT PPM-DOM installed in the Instrumentation Line of ANTARES.

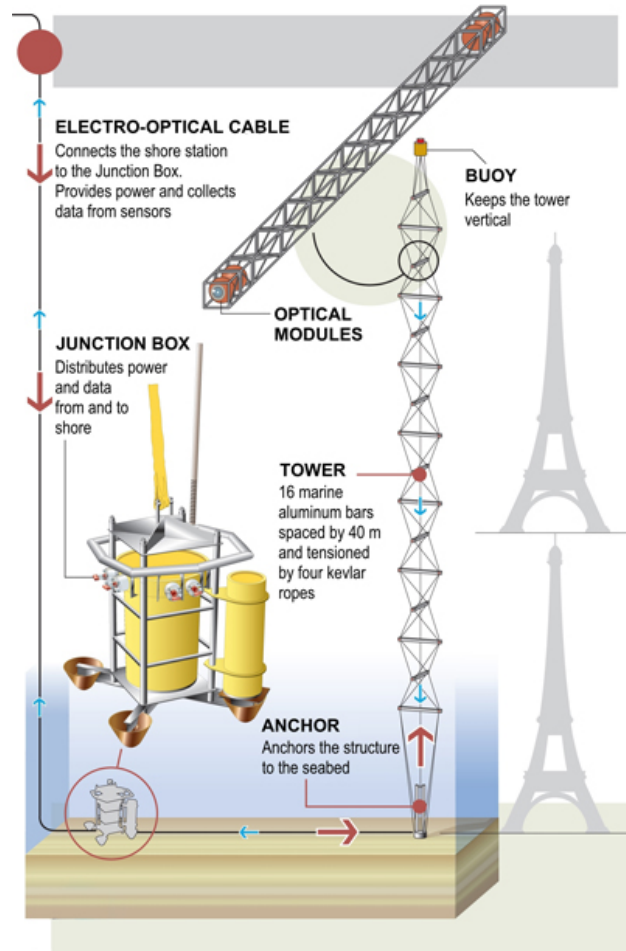


Figure 18: Scheme of the Nemo Phase II tower, installed in Capo Passero in March 2013.

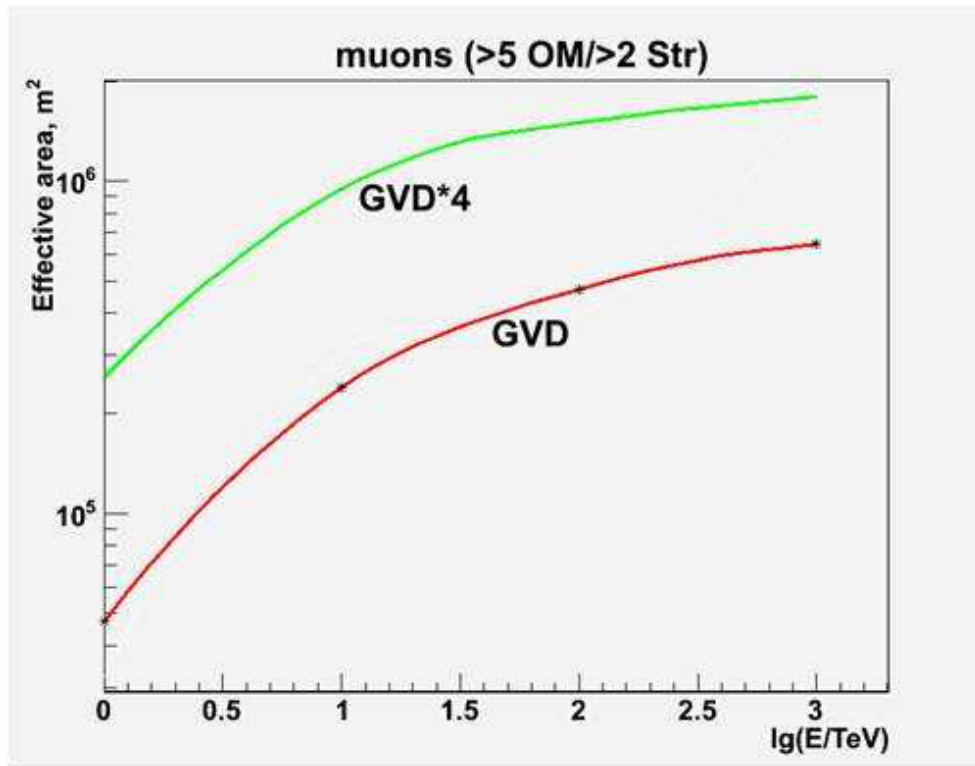


Figure 19: Projected effective area as a function of the energy for the Baikal-GVD detector at two different states. The total planned number of PMTs is 10368.